IOP Publishing   *Environ. Res. Lett.* **15** (2020) 104063   https://doi.org/10.1088/1748-9326/abae29

Environmental Research Letters

OPEN ACCESS

RECEIVED
24 March 2020

REVISED
10 July 2020

ACCEPTED FOR PUBLICATION
11 August 2020

PUBLISHED
6 October 2020

LETTER

Global distribution and cleanup opportunities for macro ocean litter: a quarter century of accumulation dynamics under windage effects

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Keywords: ocean litter, windage effect, forward-tracking simulation, ocean service

Supplementary material for this article is available online

Abstract

Ocean litter is of growing global concern, and its impacts on marine environments and ecosystems are expected to increase further this century. From a management perspective, natural drifting of macro ocean litter to or near the coast may have a relatively easier opportunity to be cleaned up directly from land, which then helps eliminate litter sufficiently and reduces the associated societal costs. However, quantitative descriptions both of the potential arrival areas of accumulation and of the cumulative impacts of ocean litter and services are lacking. The wind is critical to restructuring litter distributions in locations greatly different from those within the gyres where litter is typically found, prompting strong concerns regarding previously ignored areas, especially the equatorial zone and northern polar regions. As the windage increases, litter is transported across oceans, and polar oceans would become a litter sink instead of a source when litter is simulated to originate from both offshore and coastal areas. Different proportions of offshore- and coastal-source litter exhibit different terminal configurations, including floating offshore, floating near the coast and washed ashore. Notably, depending on windage, 78.4%–94.0% and 54.1%–56.1% offshore- and coastal-source litter continue moving in the oceans. Furthermore, important consequences associated with global marine biodiversity priority areas and litter accumulation are identified, as are substantial increases in influences on phytoplankton biomass with increasing windage. The results not only improve our understandings of macro ocean litter accumulation but also reveal opportunities for proactive prevention and planning of cleanup efforts with relatively low costs regardless of the ocean litter's offshore or coastal origins and can provide support for regional-to-global actions and policies addressing the contemporary impacts of macro ocean litter on environments.

1. Introduction

Ocean litter, consisting of direct and indirect anthropogenic waste discarded in the oceans, has drastically increased recently and become a critical challenge for the global community due to its multifaceted effects on the environment, life, human health, and society (Thompson *et al* 2009, Cole *et al* 2011). In open oceans, observations and simulations have indicated that ocean litter converges in large-scale subtropical zones by wind-driven Ekman spirals and geostrophic circulations, forming so-called 'garbage patches' (Lebreton *et al* 2012, Maximenko *et al* 2012). Evidence of dynamic concentration of floating litter along ocean areas close to land often remains complex and contradictory (Law *et al* 2010, Ryan 2015, van Sebille *et al* 2015). Besides, more than 80% of related studies have confirmed that ocean litter affects one or more biological levels (atoms to ecosystems) and biological scales from individual to ethnic groups (Barnes 2002, Oehlmann *et al* 2009, Browne *et al* 2015). Accordingly, a chain reaction occurs when a living creature is exposed to excessive amounts of ocean litter; this can cause considerable disturbances, driving living creatures from their typical habits (Barnes 2002, Oehlmann *et al* 2009). Ecological structures (e.g. clustering and food webs) and processes (e.g. competition and predation) are altered through bioaccumulation potential of toxicity over generations, damaging the ecosystem services provided by the ocean (e.g. the biogeochemical cycle, Oehlmann *et al* 2009, Browne *et al* 2015). Nevertheless, whether the aforementioned reactions can be mitigated or restored through management is still unknown. In addition to the international regulation of the use of disposable consumer materials and the development of environmentally friendly products to limit the amount of litter and plastic debris entering the marine environment (EC 2018a, 2018b), identifying hotspots of accumulation and providing quantitative descriptions of open ocean areas are necessary. Undoubtedly, litter clearance is a vital task for mitigating related effects on the marine environment. If the accumulation of ocean litter can be considered at a global scale, international cooperation can effectively aid in protecting the marine environment.

Litter sinking and floating in shallow ocean waters is affected mainly by ocean currents and winds (the so-called windage effect) and is also highly related to the characteristics and types of the litter (Law *et al* 2010, Lebreton *et al* 2012, Maximenko *et al* 2012, Duhec *et al* 2015, Allshouse *et al* 2017, van Sebille *et al* 2020). For example, fishing nets and small furniture floating underwater are generally recognized as uninfluenced by winds and regarded as low-windage materials, whereas the transportation of Styrofoam, empty plastic bottles, and fishing buoys with low density, which are thought of as high-windage ones, are strongly modulated by winds (Duhec *et al* 2015, Allshouse *et al* 2017). Currents control the movement of litter below the ocean surface with a characteristic surface speed of dozens of centimeters per second, while winds tow the portion of litter exposed to the air with a global average 10 m wind speed of 6.64 m s^{-1} measured over the ocean (Rao 2019); therefore, the effects of both aforementioned resistances must be simultaneously considered. The coaction of ocean currents and winds, which accelerate/decelerate the original flow of litter exposed to the air due to similarities/differences in direction, determines the transportation of ocean litter, further affecting the ecosystems of areas that the ocean litter passes through. Besides, inconsistent projections of changes in atmospheric and oceanic circulations caused by climate change may lead to an ocean litter scenario worse than that related to current assumptions (Valley *et al* 2017, Moemken *et al* 2018, Thornalley *et al* 2018).

The ocean covers most of the Earth's surface and provides unique and important services as well as essential resources for humans and other living creatures (Barbier 2017). Studies found that ocean litter pollution has reduced marine ecosystem service delivery by at least 1%–5%, including fisheries, aquaculture, climate regulation, pest and disease control, heritage values, aesthetics, and recreation, for an annual loss of US$500−2500 billion to society (Barbier 2017, Beaumont *et al* 2019). More active measures must be taken to understand the damage to the marine environment caused by ocean litter and to ensure that the marine environment maintains its health under this severe challenge. The need to further examine how the spatial and temporal effects of ocean litter correspond to other environmental or economic factors, including marine phytoplankton biomass, fisheries activities, and marine biodiversity, was considered together in this study to improve the comprehensive protection of the marine environment. The three aforementioned factors that are evidenced and/or expected to be impacted to some extent by the presence of ocean litter were regarded as examples of marine ecosystem services in this study (Sigman and Hain 2012, Deudero and Alomar 2015, Beaumont *et al* 2019). Chlorophyll, as a vital photosynthetic pigment in relation to phytoplankton biomass, largely determines the photosynthetic capacity and source of energy for plant growth and provides a proxy for primary production, which, in turn, provides and maintains the energy balance of ecosystems (Sigman and Hain 2012, O'Reilly and Sherman 2016). Due to a rapid increase in our dependence on protein supplied by the ocean, fisheries catches affect the global food economy. Automatic identification systems expand opportunities for using spatiotemporal data related to fishery activities (Kroodsma *et al* 2018). The marine environment has a high level of phyletic diversity; its biodiversity is considered as a main factor determining the long-term stability of the ecosystem and its ability to recover from major disturbances (Jenkins and Van Houtan 2016).

Here, using forward-tracking simulations of the past 25 years to explore the impact and challenge of contemporary emerging environmental issues, we provided a global assessment of macro ocean litter accumulation underlying the windage effect. According to simulation results covering all oceans and overlapping with crucial services related to the marine environment, this study aimed to identify areas that were most affected by macro ocean litter to provide global ocean litter management strategies and vital data for response measures. In particular, this study (1) analyzed the possible accumulation scenarios of ocean litter from 1993 to 2017 and recorded litter distributions at a spatial resolution of 1/3° in each ocean area to determine the hotspots of ocean litter, (2) assessed changes in the accumulation of offshore-and coastal-source litter in the past 25 yr to examine the spatial and temporal trends of global ocean litter accumulation, and (3) derived geographically explicit information regarding the cumulative effects of ocean litter by combining litter accumulation areas, marine phytoplankton biomass, fisheries, and marine biodiversity.

2. Methods

All variables and estimations were bilinearly interpolated to a quasi-global 1/3° × 1/3° equal-area grid as that used in the Ocean Surface Current Analysis Real-time (OSCAR, Bonjean and Lagerloef 2002, Johnson *et al* 2007).

2.1. Quasi-global ocean surface currents and winds

The ocean surface current data were taken from the OSCAR (Bonjean and Lagerloef 2002, Johnson *et al* 2007), which is provided by the Physical Oceanography Distributed Active Archive Center, Jet Propulsion Laboratory, National Aeronautics and Space Administration (PO.DAAC, JPL, NASA; https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg). The ocean surface currents directly estimated from the satellite remote-sensed sea surface height, sea surface wind, and sea surface temperature took into consideration the geostrophic, Ekman and Stommel shear dynamics and a complementary term from the surface buoyancy gradient. The data available since October 1992 cover a quasi-global area between 80°S and 80°N with a horizontal resolution of 1/3° × 1/3° and a temporal interval of 5 d. We adopted the area between 68°S and 68°N to carry out the forward-tracking simulations for less uncertainties caused by the ice formation/melt in the polar ocean regions.

The gridded surface vector winds were computed based on the Cross-Calibrated Multi-Platform (CCMP) version 2 product (Atlas *et al* 2011), which is produced by the Remote Sensing Systems using satellite microwave winds, instrument observations at moored buoys, and reanalysis wind data (The European Center for Medium-Range Weather Forecasts ERA-Interim Reanalysis winds) and is available at www.remss.com. The wind records available since January 1987 have a quarter degree resolution with quasi-global coverage between 78.375°S and 78.375°N and a temporal interval of 6 h. Both the ocean surface currents and gridded surface vector winds from January 1993 to December 2017 were extracted to further perform the following forward-tracking simulations in this study.

2.2. Forward-tracking simulations

Using the OSCAR ocean surface currents and CCMP ocean surface winds, we carried out the forward-tracking simulations in order to investigate the potential destinations of macro ocean litter. The forward-tracking formula was as follows:

$$\vec{X}_{t+1} = \vec{X}_t + \vec{U}_t \cdot \Delta t$$

where t and Δt were the time and time interval of the input data, $\vec{X}_t$ and $\vec{U}_t$ were the location of the particle and flow at time t, and $\vec{X}_{t+1}$ was the predicted location of the particle at time $t + 1$. Considering both the effects of ocean flow ($\vec{U}_c$) and wind ($\vec{U}_w$), $\vec{U}_t$ could then be divided into two components:

$$\vec{U}_t = \vec{U}_c + C_w \cdot \vec{U}_w$$

where C_w, the coefficient of windage effect, typically ranges between 0 and 0.05 depending on the size, degree of aerial exposure, and other physical attributes of materials (Duhec *et al* 2015, Allshouse *et al* 2017). The windage effect expresses how large the ocean surface winds can directly drag the litter in addition to the advection of ocean currents, and is generally classified into low ($C_w = 0$–0.01), moderate ($C_w = 0.02$–0.03), and high ($C_w > 0.04$), jointly representing the characteristics of macro ocean litter in this study, such as fishing nets, small furniture, bottles floating below the ocean surface, which are not directly affected by winds; litter items such as capped plastic bottles partially filled with water, shoes, and empty capped glass bottles that move in the ocean and are affected by both the ocean surface currents and winds; and litter items such as Styrofoam, empty plastic bottles, and fishing buoys with low density that float on the surface of the water and are primarily driven by winds.

By assuming that macro ocean litter items could be produced/thrown anywhere, including from terrestrial source (*i.e.* defined the litter movement of originating from coasts in the following analyses) and the litter onboard (*i.e.* defined the litter movement of originating from offshore in the following analyses), the forward-tracking simulations were first established by randomly releasing ten particles. Each particle was regarded as virtual individual litter hereafter, in a 1/3° × 1/3° equal-area grid in the global ocean areas between 68°S and 68°N. After being released, each litter item was continuously tracked until it was washed ashore or passed the northern or southern boundaries, *i.e.* 68°N or 68°S, and the overall simulation until a simulation date of December 31, 2017 was then conducted and terminated. For simplifying the simulations, the initial dates of releasing litter were set to the first days of January, April, July, and October in the 25 yr from 1993 to 2017; that was, a total of 100 experiments were carried out for a given windage effect. Four windage coefficients, 0, 0.01, 0.03, and 0.05, were selected to clarify the windage effects on the distributions of macro ocean litter or, in other words, whether macro ocean litter with different windage effects would ultimately accumulate in the same regions or not (Duhec *et al* 2015, Allshouse *et al* 2017). To explore the movement of litter originating in different ocean areas, each grid was defined separately as offshore and coast, the latter describing grids adjacent to grids belonging to terrestrial areas. Although the windage effect may decay over time on most of macro ocean litter in a real world, how the windage effect would change with time is a challenge to be considered in the trajectory simulation due to variant characteristics (e.g. size, material quality, etc) of litter. Therefore, the windage-effect coefficients were kept constant throughout the simulation period in the study. Additionally, we assumed that the actual changes of macro ocean litter accumulation would be ranged between our windage-effect scenarios. If the windage effect decays, the distributions of actual macro ocean litter accumulation could be close to the results under the zero and low windage effects, *i.e.* $C_w = 0$ and 0.01.

2.3. Global distributions of ocean services

We compiled a database of ocean color from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) as launched by the Orbital Sciences Corporation on the OrbView-2 (a.k.a. SeaStar) satellite, operated from 1997 to 2010, and conducted by NASA to provide a reference of marine phytoplankton biomass and a proxy for primary productivity (O'Reilly and Sherman 2016, Sigman and Hain 2012). The SeaWiFS collected global data at 4 km resolution and local data (limited onboard storage and direct broadcast) at 1 km resolution. The average annual rates of fishing activities during the 2012–2016 time period were obtained from globalfishingwatch.io based on original daily fishing effort at 0.1° resolution from digital maritime mobile service identity (MMSI) tagging unique to each vessel (Kroodsma *et al* 2018). The 500 m resolution marine biodiversity priority data were organized by Jenkins and Van Houtan (2016), who suggested and mapped the top marine conservation areas that are considered in terms of species vulnerability, coverage by marine protected areas, and human impact.

2.4. Statistics

For each windage coefficient, we calculated the proportions of the total litter accumulation within a quasi-global 1/3° × 1/3° equal-area grid on the last day of each year during 1993–2017. We computed the annual analysis and the relative change in ocean litter accumulation estimates as $\triangle = (\text{Accumulation}_n - \text{Accumulation}_m)/\text{Accumulation}_m \times 100\%$, where m and n are consecutive years. A 5° moving average was then calculated to obtain geographical changes of macro ocean litter accumulation along longitudes and latitudes to compare differences among the four windage effects. The world's ocean was divided into seven major subregions, including the north/south Pacific Ocean, north/south Atlantic Ocean, north/south Indian Ocean, and Southern Ocean (SO), to understand the dynamics of macro ocean litter accumulation and movement and the influence of the windage effects on each ocean subregion. To account for the geographical consistency in macro ocean litter accumulation and ocean services, we quantified and overlapped the top 25% areas under each ocean service and under the windage effects.

3. Results and discussion

Simulated accumulation of macro ocean litter reasonably demonstrated its severe occurrence in all ocean areas of the world as well as considerable variability in accumulation percentage, with hundreds of 1000-fold differences between certain areas (figure 1, supplementary data figures 1–4 (available online at stacks.iop.org/ERL/15/104063/mmedia); max.-min. ratio between grids until 2017: 239 987.4, 324 298.4, 344 027.6, and 640 958.4 under the windage effects, $C_w = 0$, 0.01, 0.03, and 0.05, respectively). We generally found that the ocean litter became more concentrated over time, while the litter distributions shifted with increasing windage effect. With increasing windage effect, the accumulation patterns gradually shifted concentrated areas from the subtropics to the tropics and high latitudes in both the Northern and Southern Hemisphere; in particular, the Pacific Ocean contained the most severe accumulation areas with intensively high concentrations ($>0.1 \times 10^{-4}$%) relative to other oceans. The Pacific litter accumulation transferred from the east coast to the west coast and increased to the highest cumulative percentage, and the equatorial region of the Pacific Ocean and offshore northeastern Australia were particularly predicted to be heavily covered and impacted by macro ocean litter. Conversely, the accumulation of macro ocean litter in the Atlantic and Indian Ocean was widely reduced. Notably, the first 3 yr, *i.e.* 1993–1995, exhibited strong changes, but the range and quantity of macro ocean litter accumulation were generally stable over the next 20 yr, implying that litter randomly thrown into the ocean may on average take 3 yr to become redistributed or concentrated by ocean currents/winds.

From a management perspective, natural drifting of macro ocean litter to or near the coast may have a relatively easier opportunity to be cleaned up directly from land, which then helps eliminate litter sufficiently and reduces the associated societal costs. On the basis of simulated macro ocean litter accumulation, we therefore predicted accumulation shifts in consecutive years since 1993 by calculating the trajectory over which the windage effects were assumed to exhibit values of 0, 0.01, 0.03, and 0.05, respectively, based on offshore and coastal release areas, *i.e.* offshore- and coastal-source litter, and exploring the litter arrival areas. We found that the windage was

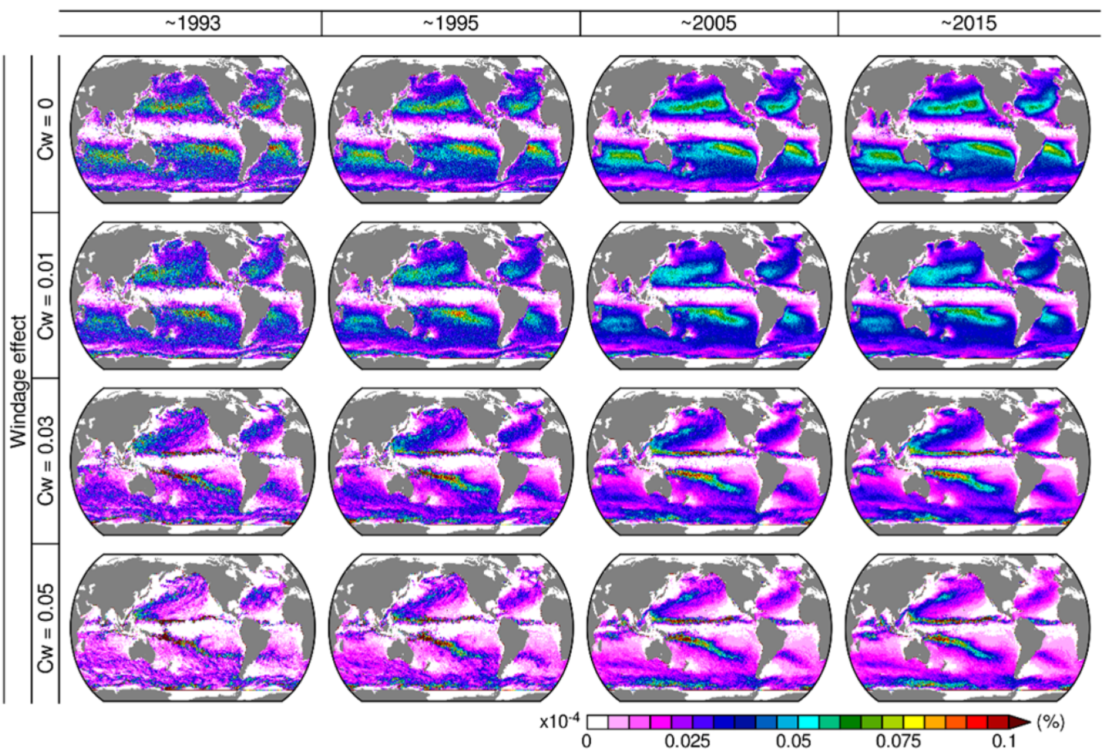

Figure 1. Spatial patterns of simulated macro ocean litter accumulation up to 1993, 1995, 2005, and 2015 under four different windage effects, *i.e.* $C_w = 0$, 0.01, 0.03, and 0.05. Values are measured as the proportions of litter accumulation within a grid on the last day of each year. White colors represent no accumulation in litter. For other details of annual simulated macro ocean litter accumulation under each windage effect, see supplementary data figures 1–4.

an important factor pushing litter to the shore and landing; otherwise, litter would continue to move and cycle in the oceans with ocean currents (figure 2). In the case of the simulation without windage ($C_w = 0$), approximately 4% of the litter released offshore could land between 1993 and 2017, while the rest continued drifting in the coastal or offshore areas. The sum of the percent frequencies of litter released offshore for landing and floating near the coast increased in multiples as the windage effect increased (13%–14% and 12%–13%, respectively, when $C_w = 0.05$). In addition, 27%–31% of the macro ocean litter released near the coast landed, and of the remainder, more than half was still floating in the coastal or offshore areas. In general, stronger winds exerted greater energy to deliver litter to the coastal areas and further induce landing, and higher-windage litter was more easily driven toward land by winds. However, unlike the offshore-source litter, our results broadly confirmed that the coastal-source macro ocean litter was little affected by winds, and the variations in each windage effect were smaller than those from offshore areas.

In addition, over time, periods of decreasing and increasing litter that ended up in different areas varied and showed limited consistency (figure 2 inset plots). The average relative annual changes in offshore-source litter that ended up continuously floating offshore, floating near the coast, and being washed ashore, were 0.02%, −0.29% and −0.11%, respectively, without windage ($C_w = 0$), and increased to 0.08%, decreased to 0%, and increased to −0.23%, respectively, under a high windage effect ($C_w = 0.05$). The corresponding annual changes ranged from 0.23% to 0.29%, −0.07% to −0.12% and −0.09% to −0.13%, respectively, when litter was released near the coast. The litter outflowing from the simulation boundaries occupied a certain proportion (average changes for 1993–2017 from 2.4% to 9.27% with the windage effect changing from 0 to 0.05 when released offshore and from 14.18% to 15.85% when released near the coast) and exhibited drastic relative changes in the initial years, implying that the litter accumulation and its subsequent threats in the northern polar ocean regions may increase rapidly. Analysis of a subset of samples showed evidence that increasing exploitation of Arctic resources will likely lead to a higher litter load in the Arctic sea ice (Cózar *et al* 2017, Peeken *et al* 2018).

We also integrated the spatial variations in the magnitude and direction of latitudinal and longitudinal velocities of macro ocean litter accumulation over time. Litter released from offshore areas showed larger variations along both longitudes and latitudes under different windage effects than that released near the coast (figure 3, supplementary data figures 5–6). Simulated accumulation of offshore-source litter continuously floating offshore based on zero and low windage effects, *i.e.* $C_w = 0$ and 0.01, showed a latitudinal peak at approximately 30°N and 25–50°S and widespread areas of low accumulated litter

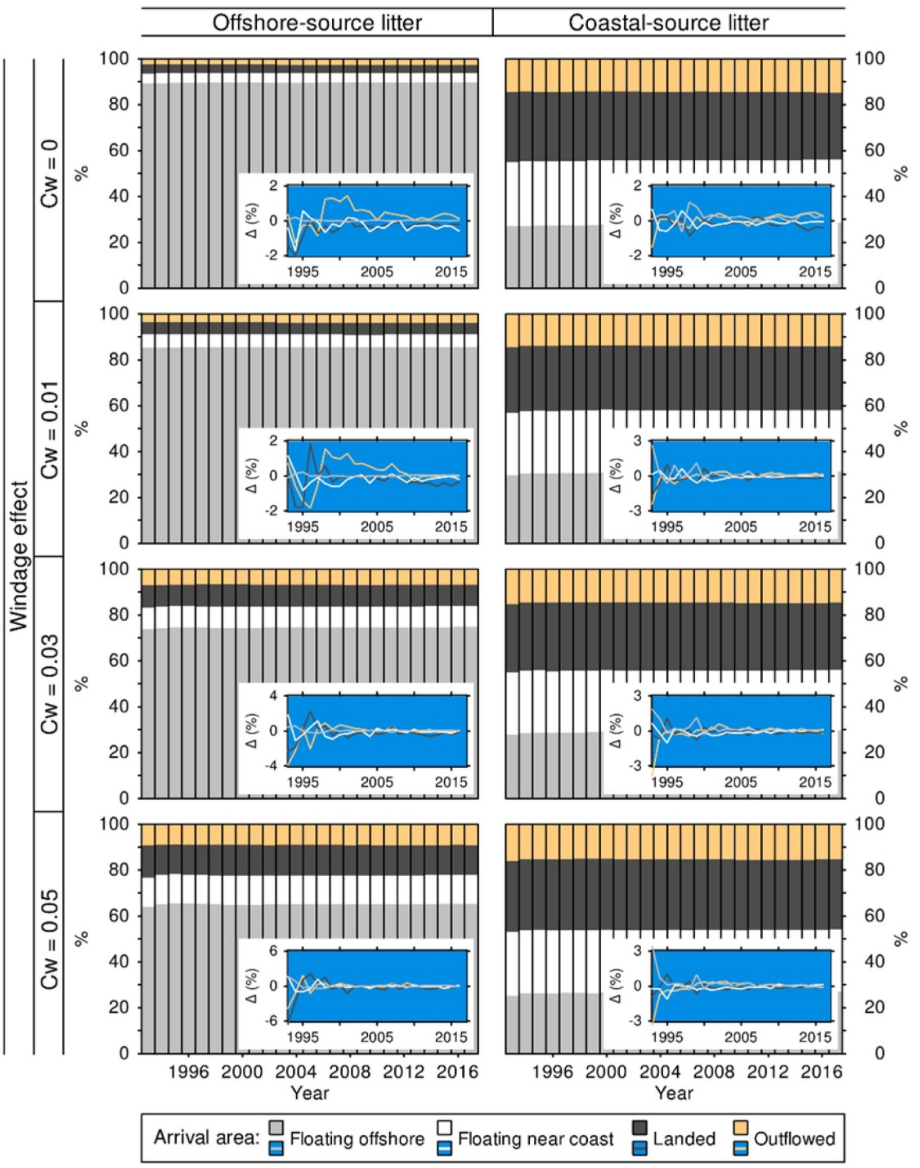

Figure 2. Temporal trends of arrival areas under four different windage effects on simulated macro ocean litter accumulation released offshore and near the coast, respectively, between 1993 and 2017. Light-gray, white, dark-gray, and yellow shading denote litter, respectively, being floating offshore, being floating near the coast, having landed, and having outflowed from the simulation boundaries (*i.e.* mainly from the North Atlantic Ocean to the Arctic Ocean) on the last day of a year. The inset plots provide temporal trends in the annual relative changes for different windage effects (△, %).

concentrations near the equator, whereas an extreme peak was predicted at 10°N and >60°S based on moderate and high windage effects, *i.e.* $C_w = 0.03$ and 0.05, concentrated in the Central Pacific as previously mentioned. This pattern is consistent with that inferred from recent observations of ocean litter accumulation worldwide since 2006 (Schwarz *et al* 2019, and references cited therein). Moreover, high rates of extirpation are expected for equatorial species under moderate warming given their narrow thermal tolerance ranges and comparatively low capacity for acclimatization (Molinos *et al* 2016). If coupled with the damage caused by the accumulation of ocean litter, disturbance on wildlife population and distributions may probably increase. Interestingly, the offshore-source litter also showed high landing possibilities at 10°N and additionally at 5–15°S under each windage effect. The relatively even distributions of coastal-source litter accumulation along latitudes and longitudes re-emphasized this global environmental threat (Lebreton *et al* 2019), and the high latitudes in the Southern Hemisphere seemed to show the greatest vulnerability to such ocean litter problems.

Our simulations predicted strong changes along latitudes but limited variations along longitudes in global patterns of accumulation of litter floating and landing for offshore and coastal release areas, robust to underlying variability in expected influences by ocean currents under the zero and low

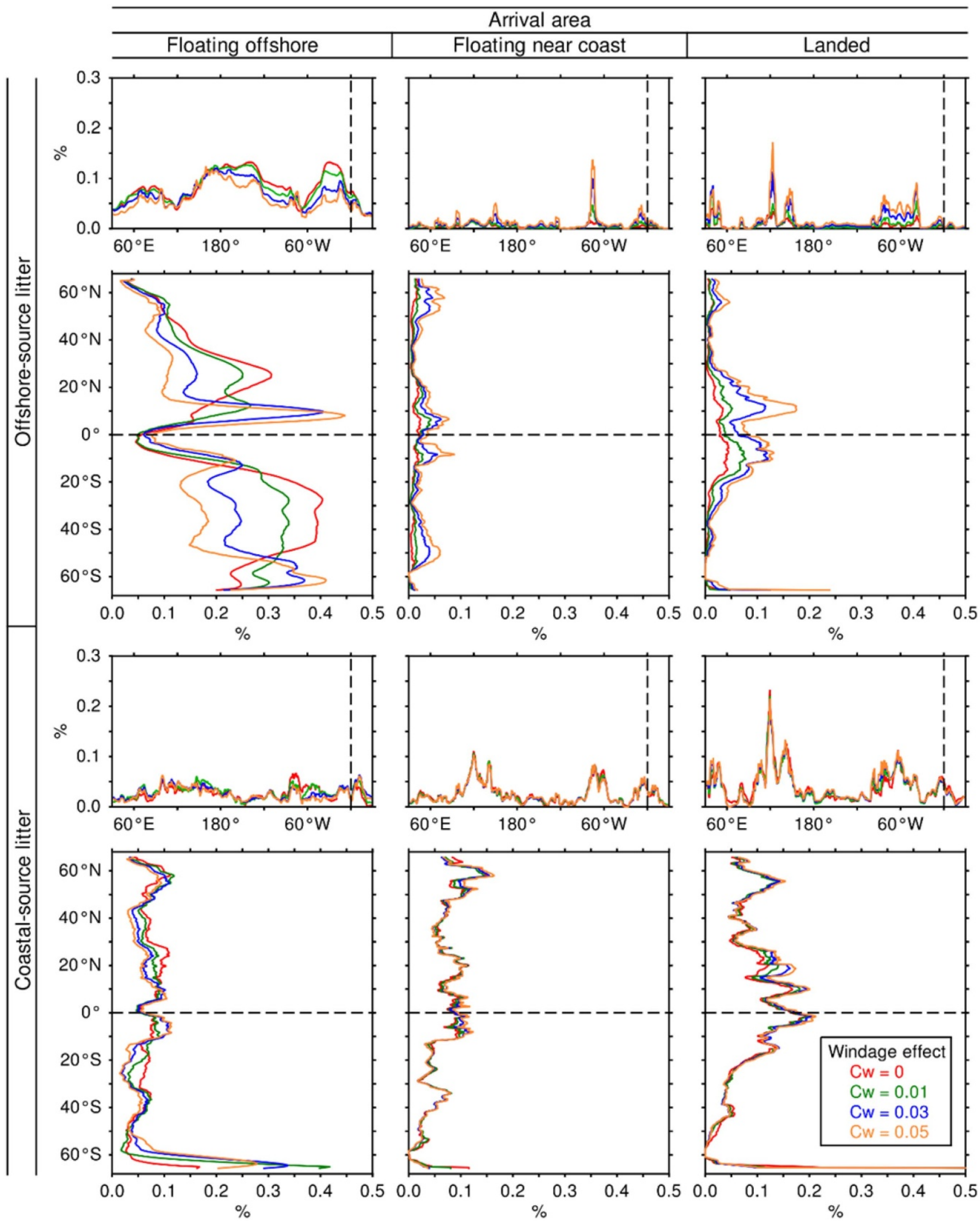

Figure 3. Simulated zonal distributions of arrival areas of macro ocean litter accumulation until 2017 under four different windage effects, *i.e.* $C_w = 0$, 0.01, 0.03, and 0.05, released offshore and near the coast, respectively, between 1993 and 2017. All curves are smoothed by a 5° moving average. The dotted lines indicate the equator and the prime meridian. For simulated longitudinal and latitudinal distributions of macro ocean litter accumulation by years, see supplementary data figures 5–6.

windage effects, when the litter came from offshore but with contrasting outcomes under the moderate and high windage effects, when the litter came from the coast. The results based on the low windage and offshore-source litter were in general agreement with previously predicted patterns, not only highlighting the pivotal role of ocean currents on litter accumulation and supporting the reliability of our model but also implying that the simulation results for relatively high windage effects, *i.e.* $C_w = 0.03$ and 0.05, need to be carefully considered. Recent evidence suggested that the systematic forces of ocean currents and winds are not a global driver of the temporal change in the rates of present-day ocean litter accumulation, but urban development and inequality in environmental management would result in the accumulation of different litter abundances (Andrady 2011, Cózar *et al* 2014); we predicted that this state will hold into the future. Although the litter accumulation was predicted by simulations to be regionally important, they

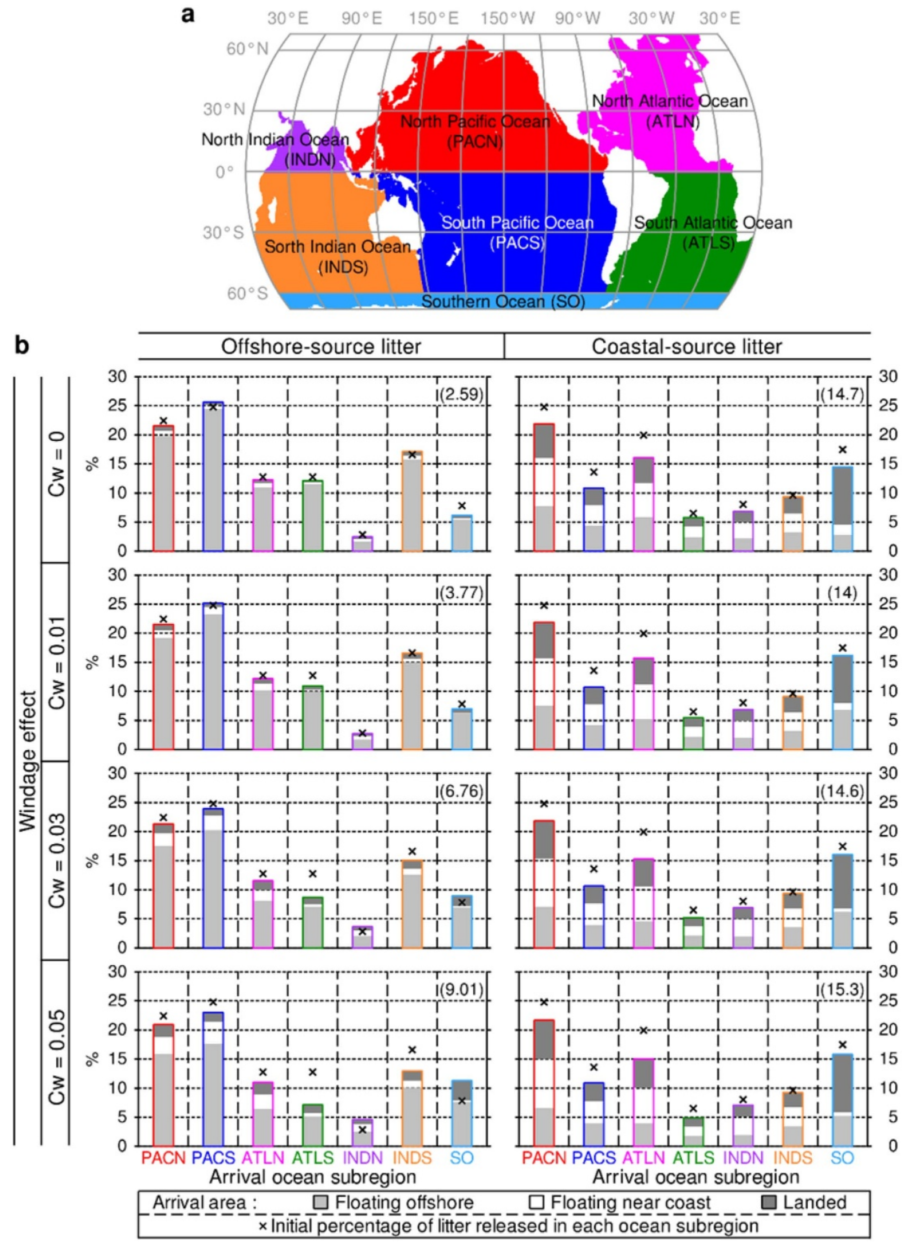

Figure 4. Frequency distributions of ocean boundary-scale patterns of simulated macro ocean litter accumulation up to 2017. Bar marginal color at the *x*-axis, which indicates the arrival ocean area for the litter, relates to separation of the world's oceans into seven major subregions in (a). In (b), cross points represent the initial percentage when releasing litter offshore and near the coast, respectively, in each ocean subregion. Percentages of macro ocean litter flowing out from the simulation boundaries, *i.e.* mainly from the North Atlantic Ocean to the Arctic Ocean, are labeled on the upper-right corner of each panel.

are combined with economic and biological impacts that ultimately mediate the vulnerability of marine environment.

Differences were observed in a comparison of the proportions of macro ocean litter accumulation in the three arrival areas among the seven major subregions of the world's oceans (figure 4), although the results were generally similar to the global patterns revealed in figure 2. For individual subregions, greater changes were observed under the moderate and high windage effects for litter originating in the offshore areas. More litter in the North Pacific Ocean (PACN), the South Pacific Ocean (PACS), the North Atlantic Ocean (ATLN), the South Atlantic Ocean (ATLS), and the South Indian Ocean (INDS) left its original oceans and then entered the North Indian Ocean (INDN) and the SO as the windage effect increased, indicating the important role of wind in transporting litter across oceans. In addition, when the windage effect became stronger, more litter escaped the simulation boundaries in the ATLN and mainly flowed to the Arctic Ocean subsequently. Moreover, winds transported ocean litter in the Pacific Ocean and Atlantic Ocean southward to the SO and delivered the litter in the INDS northward to the INDN and southward to the SO. The unique oceanic and atmospheric dynamics of the INDS had been demonstrated a very different evolution of the accumulation of buoyant

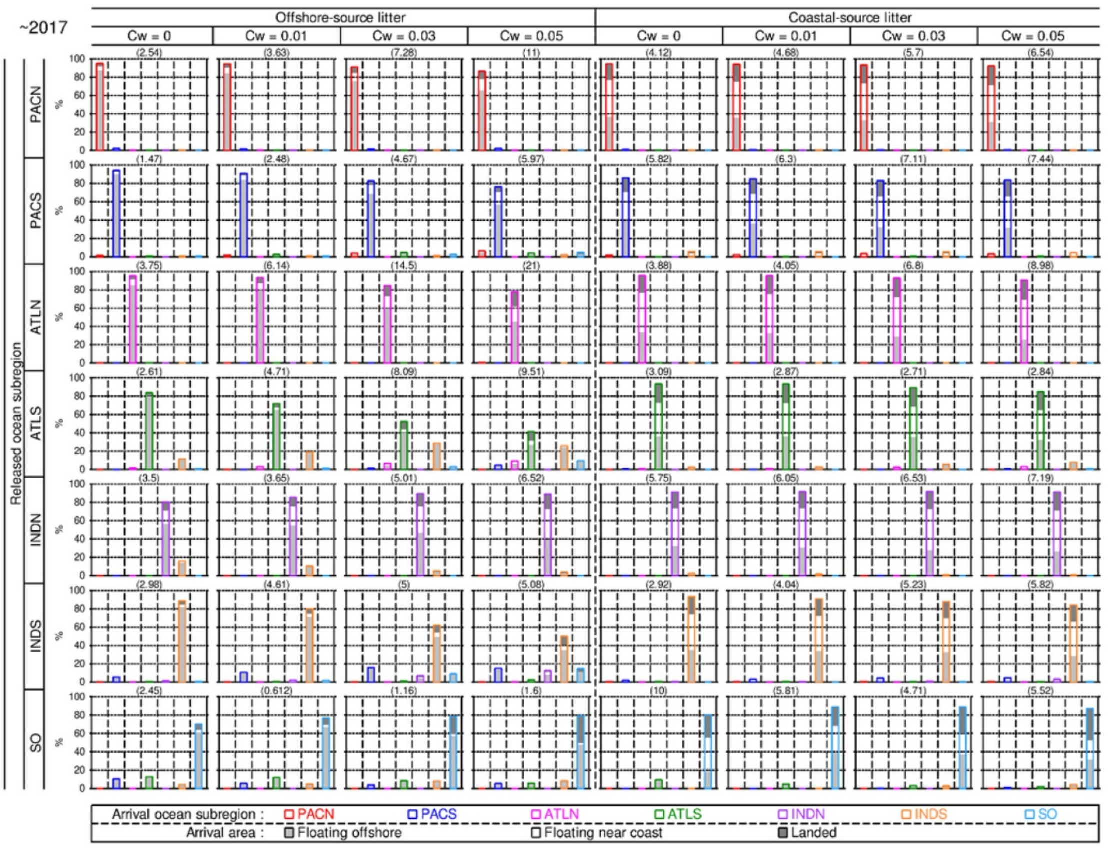

Figure 5. Frequency distributions of individual ocean boundary-scale patterns of simulated macro ocean litter accumulation after being released offshore and near the coast, respectively, up to 2017. Bar marginal color at the *x*-axis, which indicates the arrival ocean area for the litter, relates to separation of the world's oceans into seven major subregions in figure 4(a). Percentages of macro ocean litter flowing out from the simulation boundaries, *i.e.* mainly from the North Atlantic Ocean to the Arctic Ocean, are labeled above each panel. For other details of annual frequency distributions of individual ocean boundary-scale patterns of simulated macro ocean litter accumulation, see supplementary data figures 7–30.

ocean litter debris in the area and much more sensitive to different transport mechanisms than in the other ocean basins (van der Mheen *et al* 2019). Additionally, a noteworthy feature here was that the SO and the Arctic Ocean were a source under the zero and low windage effects, whereas they became a sink under the moderate and high windage effects, although release from coastal sources in the SO could be very unlikely. In other words, more low-density or high-windage litter could be delivered to or stay in the SO and the Arctic Ocean, supporting recent observation that macro ocean litter floating around the polar oceans was mainly composed of large highly buoyant items and such high buoyant features probably aid their dispersal across the polar fronts (Cózar *et al* 2017, Suaria *et al* 2020).

Pathways of macro ocean litter originating in each ocean were compared in figure 5 and supplementary data figures 7–30. In general, most macro ocean litter stayed in its original ocean, regardless of where the litter was released. In comparisons of the various windage effects on litter released offshore with the effects of windage on litter released near the coast, the patterns showed similarity to those presented in figure 4. Litter had a greater or lesser probability of being transported to neighboring oceans depending on windage forces. The winds triggered more litter to leave the original oceans of PACN, PACS, ATLN, ATLS, and INDS but retained more litter in INDN and SO. Through the Antarctic circumpolar current (ACC) in the SO, macro ocean litter in the southern parts of the Pacific, Atlantic, and Indian Ocean was relatively likely to be brought to the other oceans, as was litter in the SO, further indicating that the ACC in the SO plays a critical transmission medium in exchanging materials among oceans.

With increased potential for windage, macro ocean litter accumulation structures in all geographic locations became increasingly different from current conditions and expectations. Finally, larger windage had significant consequences for the specific geographic patterns of overlaps of top 25% areas of ocean services; in particular, global marine biodiversity priority areas exhibited 2.03% consistently overlapping with macro ocean litter accumulation regardless of the windage. Larger windage tended to lead to larger influences on marine phytoplankton biomass/primary production, increasing overlapping percentages from 0.59% to 1.41%, not including fisheries, which are actually further sustained and

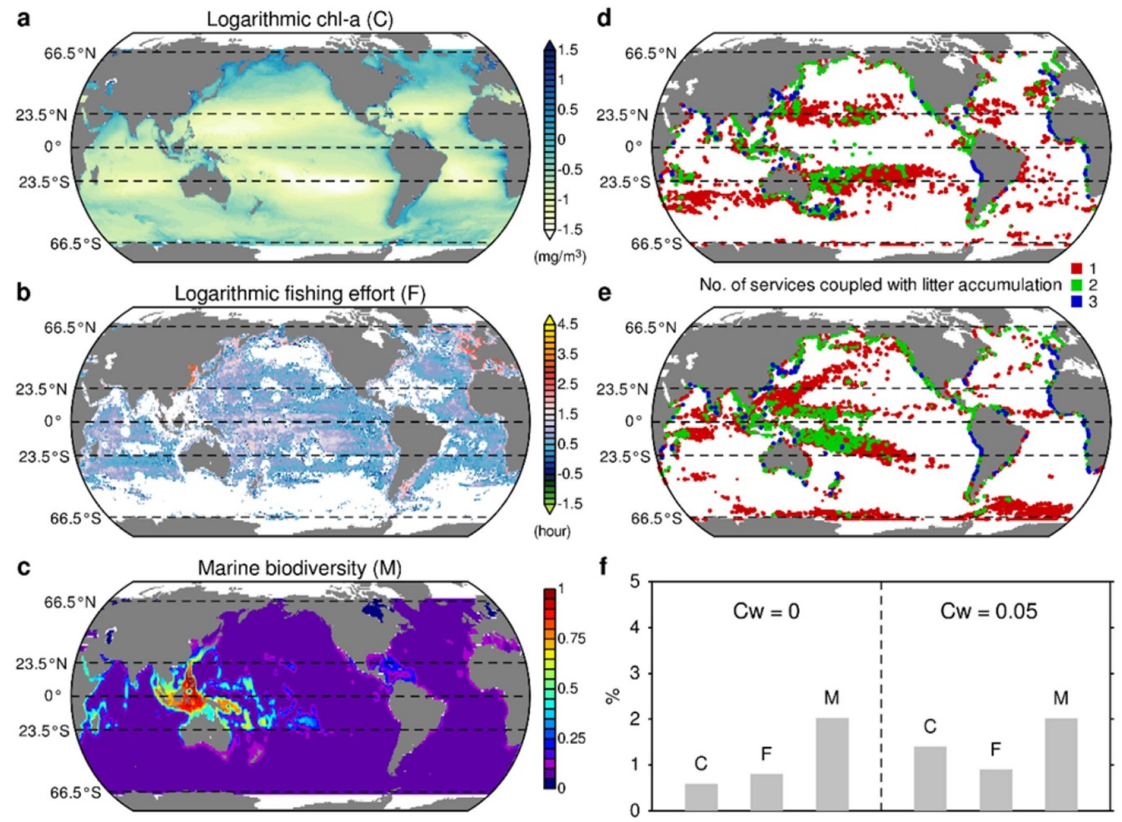

Figure 6. Global distributions of cumulative impacts among macro ocean litter accumulation and three ocean services, *i.e.* marine phytoplankton biomass shown by chlorophyll-a concentrations (C), annual total fishing effort (F), and marine biodiversity (M). (a)−(c) Global patterns of average annual chlorophyll-a concentrations, averaged annual total fishing effort in 2012–2016 by all vessels with automatic identification systems, and marine biodiversity developed priorities from the species range size and the percent of the range within marine protected areas are shown for reference. Values are logarithmically transformed in (a) and (b). (d)−(f) Overlapped top 25% footprints of macro ocean litter accumulation under zero and high windage effects, *i.e.* $C_w = 0$ and 0.05, respectively, up to 2017 with the three ocean services. Geographical matches between the distributions of one, two, and all ocean services and macro ocean litter accumulation are represented by red, green and blue, respectively.

supported by primary production as critical components; tropical increases and moderate-latitude decreases of overlaps with litter accumulation were more obvious when greater windage was assumed. In summary, the windage effect on relative litter accumulation worldwide had the potential to alter overlaps of various ocean services, especially in the coastal areas of all continents and Southeast Asia and the surrounding marginal seas, including the South China Sea, Timor Sea, Arafura Sea, and Bay of Bengal (figure 6).

This study reveals that the wind is critical to restructuring macro ocean litter distributions and greatly influences the predicted spots within the five subtropical gyres where ocean litter will wind up, prompting strong concern regarding areas that have been ignored in the past, especially the equatorial zone and polar regions. In addition, climate change poses a significant challenge for both wind energy production and the strength fluctuations of ocean conveyor belts (Valley *et al* 2017, Moemken *et al* 2018, Thornalley *et al* 2018). Stronger seasonal fluctuations and a more frequent occurrence of low wind phases as well as a further long-term slowdown of the ocean circulations overturning are expected, not only raising the risks of damaging storms along coasts and affecting the Earth system but also causing exceptional ocean litter accumulation in the coming decades under synergistic effects. Additionally, concerns have been raised that the patch size of buoyant ocean litter may be unevenly distributed over time due to population and economic growth, the quality of waste management systems and unequal use in ocean areas (Cebeci *et al* 2012, Jambeck *et al* 2015, Kroodsma *et al* 2018), such as shipping and fishing activities, and that the density of buoyant ocean litter may increase over time due to rapid biofilm formation and subsequent aggregation of fouling organisms (Rummel *et al* 2017). Although global uncertainty of litter accumulation and distributions persists, our windage-effect scenarios confirm variations in the broad spatial extent and accumulation of macro ocean litter over the last 25 yr.

Another point to be raised is that certain proportions of both offshore- and coastal-source litter were simulated to continue floating in the oceans, and this litter can be expected to become micro litter through impacts with rocks, being tossed and churned by the waves, breaking down by light, and so on. Ocean debris, especially microplastics, has been recently regarded as one of major contaminants in the world's oceans (Cole *et al* 2011), and nobody truly knows how long the litter will remain in the ocean. It has been confirmed that substantial amounts of chemicals wind up in animals' tissues (Gallo *et al* 2018), and submerged microplastics have invaded the deep ocean and driven potential risks of trophic transfer within marine food chains (Carbery *et al* 2018, Choy *et al* 2019, van Sebille *et al* 2020). Furthermore, larger proportions of the offshore-source litter as predicted to exist in the open water areas will necessitate higher costs to remove. We therefore suggest that litter storage onboard vessels should be highly regulated and monitored to prevent dumping at sea, as was common in the past, and should instead be collected, shipped back and processed onshore. Implementation of Annex V of MARPOL convention with better policy enforcement, better port-reception facilities and personal awareness would be key to effectively controlling macro ocean litter. Regional-to-global action plans should be initiated, requiring a global platform to coordinate management and inform actions.

4. Conclusions

Our findings have considerable implications for the spatial prioritization of current ocean litter prevention and cleaning strategies. Importantly, the main results presented here assume that macro ocean litter is produced evenly throughout the oceans every year, which is different from the assumption where litter would be drifting randomly and/or regularly over a period of time. Nevertheless, it is still necessary to clarify relationships between the simulations and current distributions of macro ocean litter to formulate more appropriate governance strategies. The simulations shown here demonstrate how the windage effects on macro ocean litter accumulation need to be fully considered and may improve our understandings of macro ocean litter accumulation. By highlighting areas with the highest concentrations of ocean litter and that are most at risk of the coupling of multiple ocean services with macro ocean litter accumulation, our approach can assist in guiding the development of future knowledge and the capacity to establish effective action plans to address the global ocean litter issue. The appropriate governance and management of ocean litter and its impacts have become essential for future marine environmental protection and widespread changes. To this end, bringing knowledge to society, developing global platforms, and involving transdisciplinary approaches are the keys to ensuring that the environmental science-policy-practice interface successfully navigates contemporary environmental challenges.

Acknowledgment

We thank all contributors of different types of data used in this study. We also thank anonymous reviewers that made lots of insightful comments which improved the contents of this manuscript. This work was supported by the Ministry of Science and Technology (MOST), the MOST Young Scholar Fellowship Columbus Program, and the Academia Sinica, Taiwan, under grant: MOST 107-2611-M-002-005-, MOST 109-2636-B-002-006-, AS-TP-108-LM14-2, and MOST 108-2611-M-001-009-.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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